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ELECTROMETRIC AMPLIFIERS USING SUBMINIATURE TUBES

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ELECTROMETRIC AMPLIFIERS USING SUBMINIATURE TUBES /102*

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Four versions of electrometric amplifiers with subminiature tubes are discussed in this article. The band pass in three of these amplifiers is increased to 40 - 160 cps with an input resistance of 100 G ohms.

Technical data concerning the amplifiers are presented here and some special features concerning the design of economical miniature amplifiers by the use of semiconductor devices are discussed.

In addition to the conventional requirements placed on electrometric amplifiers, i.e., a high degree of sensitivity and stability, modern experimental technology places still other requirements on these amplifiers, such as a broad band, small dimensions, and low microphonics.

At an input resistance of 10^{11} ohms it is possible to obtain a uniform frequency characteristic of 0 to 150-200 cps. This result is obtained by using a corrective filter in the negative feedback circuit or by inserting a positive frequency-dependent feedback (ref. 1). The use of thermionic tubes or a combination of thermionic tubes and transistors makes it possible to reduce the power supply to units or fractions of a watt and to power the amplifier from a

*Numbers given in the margin indicate the pagination in the original foreign text.

relatively simple stabilizer using gas-discharge tubes or Zener diodes. The use of subminiature tubes and also a combination of subminiature tubes and semiconductor devices makes it possible to produce an entire amplifier in a strong unit of small dimensions. The connection of an electrometric stage to an amplifier results in a substantial decrease in the capacitance of the plate circuit of the electrometric stage, thus determining to a large extent the frequency characteristic and the stability of the amplifier. To obtain a broad band pass and a low degree of drifting it is necessary to bring the gain in the feedback loop to several hundreds of thousands and to expand the band pass of the amplifier without feedback to several kilocycles per second. The values of the plate loads in this case reach 100 kilohms and in the electrometric stage they reach several megohms. As a result of the phase shifts in the plate circuits of the multi-stage amplifiers at frequencies of the order of tens of kilocycles per second, the negative feedback becomes positive and the amplifier may oscillate. For this reason, it is necessary to reduce the parasitic capacitance to the minimum, in particular in the case of high-ohmic plate circuits. In order to compensate for the phase shifts it is usually necessary to insert corrective RC filters into the plate circuits, reducing the transconductance of the decrease in the frequency characteristic of the disconnected feedback loop to magnitudes which do not exceed 6 decibels per octave.

The sensitivity and the stability of the amplifier depend to a large extent on the parameters of the electrometric tube, such as the grid current, the level of the flicker-noise, the voltage of the microphonic effect and the /103 static coefficient of amplification μ. To reduce the effect of the noise of the second stage, μ must be considerably greater than one. The voltage due to the microphonic effect is determined not only by the type of tube but also by the stability of the design of the input circuits of the electrometric amplifier. Under the effect of the mechanical vibrations both the shocks of the high megohm resistance and the lead of the control grid can fluctuate, causing a change in the input capacitance and the modulation of the signal at frequencies of mechanical resonance usually found in the band pass. Beside the stability of the design, the method of bracing the tubes also plays a role here. It has been found advisable to attach the electrometric tube to the mounting plate by means of tight teflon tape.

Amplifiers with a low drift are usually built according to a balanced symmetrical schematic by using a double electrometric tube in the system, thus bringing about a minimum grid current. If the demands on the magnitude of the drift are not too rigid (e.g., in the majority of wide-band amplifiers), then it is more appropriate to use single-ended circuits, the dimensions of the amplifier and the input thus being reduced by approximately one half.

1. Push-Pull Amplifiers

Three varieties of push-pull amplifiers (balanced symmetrical) have been developed. Based on one of these amplifiers (see the diagram in figure 1) six samples have been produced. The three-stage amplifier uses parallel negative feedback. The first stage uses an electrometric I-1 pentode with separate outlets controlling the grids and plates. The use in the last stage of a triode operation of a pentode together with an intense feedback decreases the output resistance of the amplifier to 100 ohms. The tube filaments, the screen grid circuits and the plate circuits of the first stage are fed by the divider R_4-R_{10}. RC filters are inserted into the plate circuits of the first and second stages to equalize the frequency characteristic of the open loop.

The feedback voltages are reduced by dividers R_{23}, R_{24} and R_{25}, R_{26}. The feedback coefficient is $\beta \approx 0.5$. The feedback resistance R in the working arm equals 10^{12} or 10^{11} ohms. Switch S_1, which changes the value of R, has a polyfluoroethylene resin insulation and is placed next to the electrometric tube. A resistance $R_3 = 5 \times 10^8$ ohm is included in the circuit of the negative feedback of the compensating arm for the purpose of improving the stability of the amplifier. A feedback to the screen grid in the first stage (not blocked by capacitance of R_{13}) improves the stability of the system and the resistance of the amplifier.

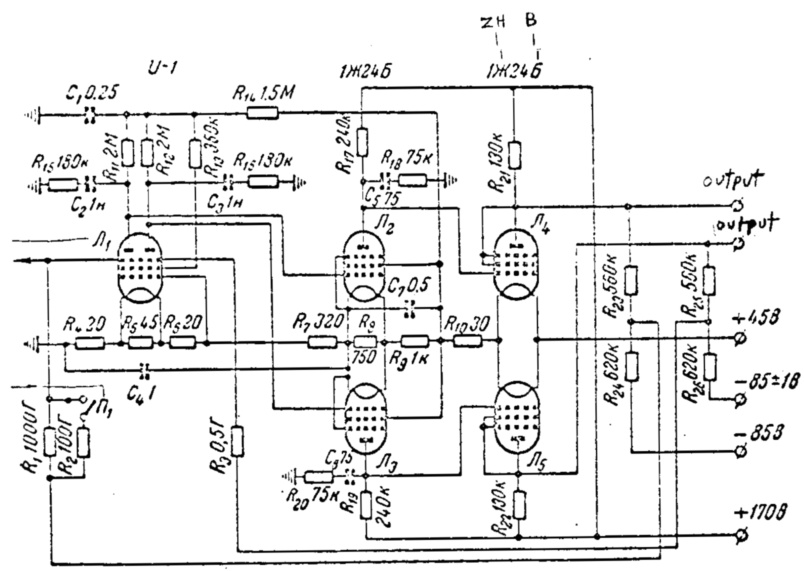

Figure 1. Push-pull electrometric amplifier with negative feedback without compensation.

A 100 microampere meter is connected between the plates of the output tube and, therefore, the amplifier output is not grounded. The supply source is obtained from a stabilizer using gas-discharge tubes providing two voltages: +170 v for the entire amplifier and -85 v for creating a bias in the feedback divider. The amplifier can also be powered by a battery. The entire amplifier is housed in a steel cylindrical sheath 80 mm in diameter and 150 mm in height and is connected by a flexible cable to the supply unit where the regulating /104 mechanisms and the output measuring device are located. Technical characteristics of the amplifier are presented in the table.

Amplifier Type	R in G ohms	K	$f_{0.7}$, cps	$I_{noise} \cdot 10^{-13}$ a; p - t - p	U_{drift}, mv/min.	$U_{output\ max.}$, V; p - t - p	Required power, watt	Relative magnitude of the microphonic effect
Push-pull	1000 and 100	1500-2000	0.3	0.01	0.05	20	5	- -
Single-ended No. 1	47	1700	50	1	- -	25	4	2-3
Single-ended No. 2	100	2100	60	1	- -	25	3	1
Semiconductor	68	300-600	40	1	- -	15	1.5	- -
Wide band miniature	100	800	160	0.5	0.1	40	1.5 0.3*	- -

* In the case of supply to the filaments from a separate battery.

2. Single-ended Amplifiers

A. Amplifier with compensated positive feedback (fig. 2). This amplifier contains four stages. The voltage of the principal negative feedback is taken from the output of the third stage and from divider R_{15}, R_{16} and the high-ohmic resistance is connected to the grid of the electrometric tube. The

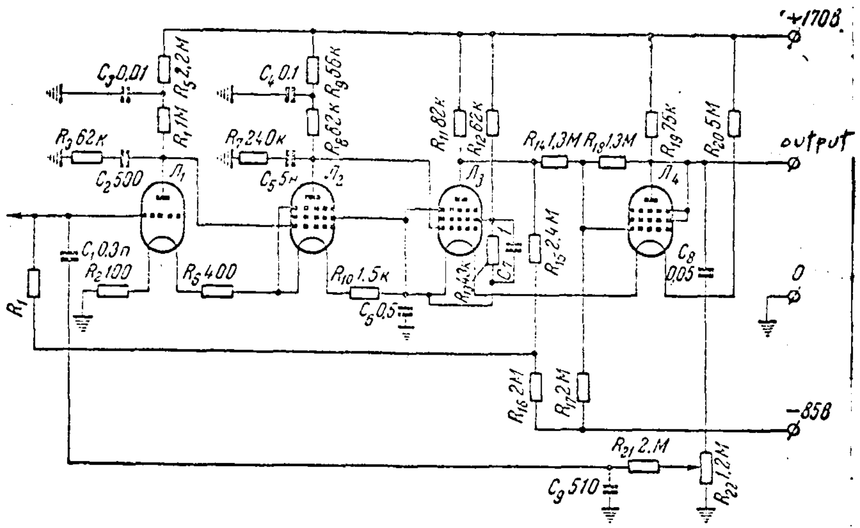

Figure 2. Single-ended electrometric amplifier with compensated positive feedback.

(Compensation: C_7 = 0.1 microfarad, R_{20} = 5 kilohms)

voltage of the compensating positive feedback is taken from the plate of the fourth stage intended to produce a phase-shift of 180° and through small capacitance C_1 (< 1 pf) is also fed to the grid of the electrometric tube. The intensity of the positive feedback is controlled by adjusting potentiometer R_{22}. The circuit of this amplifier corresponds basically to one-half of a push-pull amplifier. Only the stage which reverses the phase and a frequency-dependent divider of the feedback $R_{21}C_9$ have been added. Two types of amplifiers have been produced; they differ only with respect to the types of tubes used. In amplifier No. 1, the electrometric EM-7 triode and 1P4B pentodes were used. In amplifier No. 2, the electrometric pentode I-1 and pentodes 1Zh24B were used. The voltage stabilizer is the same as in the case of the push-pull amplifier. The entire amplifier is housed in a cylindrical three-layer case (Armco iron, copper, Permalloy) 65 mm in a diameter and 145 mm high. Such a careful screening is necessary when working in strong electromagnetic fields.

In the case of compensated amplifiers it is necessary to work out in detail the design of the input stage and its screening from the other stages, since parasitic feedbacks through the distributed capacitance can sharply narrow down the band pass or alter the form of the frequency characteristics and the transient characteristics. For this reason, the electrometric stage has additional screening with the regular case and the number of leads coupling it to the rest of the circuit is made as small as possible. /105

Amplifiers No. 1 and No. 2 are practically the same with respect to the electrical parameters (see the table), but the voltage due to the microphonic effect is 2-3 times less in amplifier No. 2. In addition to this, it is more stable with respect to the changes in the ambient temperature and humidity.

B. Electrometric amplifier with transistors, (fig.3), is composed of an EM-7 triode electrometric stage and four transistor stages with 100 percent feedback. The voltage divider feeding the individual parts of the circuit is made up of silicon zoner diodes D_1-D_4. The use of a divider of this type along with the use of n-p-n and p-n-p type transistors makes it possible to reduce the supply voltage of the amplifier and to compensate the fixed component voltage at the output. Local feedbacks in the circuits of emitters T_2 and T_3 increase the stability of the system. The band pass is increased aid of corrective filter $R_{10}C_3C_4$ in the negative feedback loop. In the process of developing the system it became obvious that the level of the inherent noises in the transistors was greater than the level of the noises in the input circuit and the first tube. In the case of the transistor noise, relatively high frequencies predominate for which the intensity of the regular negative feedback is small. Additional feedback through capacitance C_2 from emitter T_3 to the cathode of L_1 made it possible to reduce the total noise almost to the level of the noises in single-ended amplifiers No. 1 and No. 2.

A simple single-stage stabilizer with voltage stabilizer tube SG-2P serves as a supply source for the amplifier. Diodes D_1-D_4 are used to improve the stabilization of the rectified voltage. The amplifier is simple in design and does not require the selection of transistors due to the presence of local and general feedbacks. In order to test the effect of the variation in the parameters of the transistors in the adjusted amplifier, all of the four transistors were replaced, after which there was little change in the system and parameters of the amplifier.

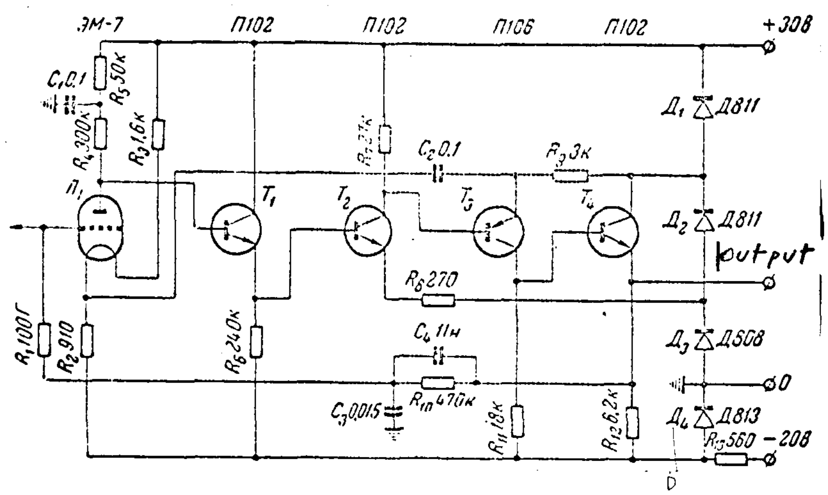

Figure 3. Single-ended electrometric amplifier with a corrective filter in the negative feedback circuit.

C. Miniature wide-band electrometric amplifier (fig. 4), contains the 1Zh42A tube electrometric stage and two 1Zh24B pentode amplifier stages. It has 100 percent feedback with a corrective filter $C_1R_{16}C_2$ which increases the frequency range. The characteristic feature of this system is the direct coupling of the filaments and the possibility of supplying them from a separate low-voltage source, thus increasing the economy of the amplifier. The coupling between the stages is carried out by dividers composed of resistances and voltage stabilizers. This makes it possible to compensate for the difference in the levels of the fixed component without incurring a loss in gain, since the dynamic resistance of the voltage stabilizers does not exceed a few ohms. A relatively high level of internal noise in the voltage stabilizer renders it unfit for work in the coupling divider of the first stage. Its noise is hardly noticeable in the following stages. The circuits of the filaments, screen grids and plates of the first stage are fed by the divider consisting of zoner diodes D_6-D_9, this also making it possible to feed the amplifier from either a battery or from the power line through a simple stabilizer. In the case of most silicon zoner diodes (especially types D-811, D-813) the region of stabilization begins with rather small currents at 10-30 microamperes. In this way it is possible to limit the divider currents composed of the zoner diodes to a fraction of a milliampere and their required power to one milliwatt. /106

The amplifier load is a 50 microampere meter with additional resistances. The output impedance of the amplifier does not exceed about 10 ohms, due to an intensive feedback. However, at high frequencies where the compensation filter reduces the intensity of the feedback the output impedance increases. Therefore, when observing rapid processes the meter must be disconnected and replaced by an oscillograph such as model ENO-1.

The entire amplifier (fig. 5) is housed in a cylindrical three-layer case 60 mm in diameter and 70 mm high. There are found in the supply unit, in addition to the stabilizer, the meter and the range switch.

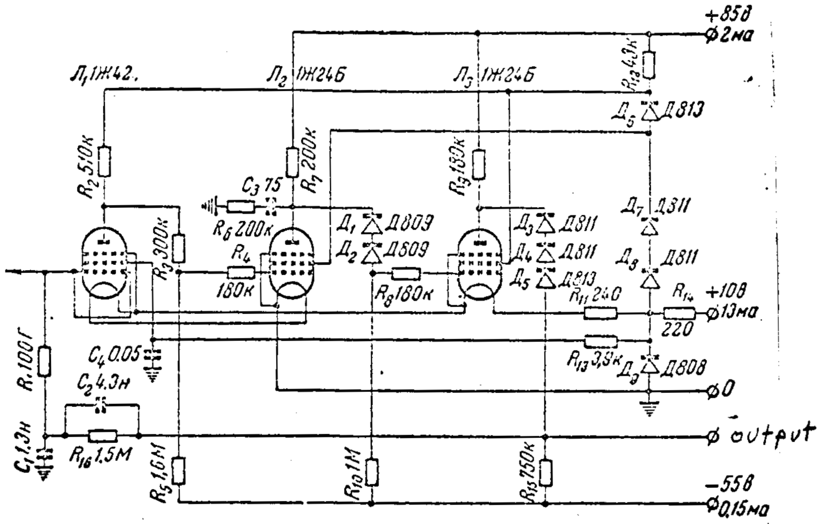

Figure 4. Diagram of a miniature broad-band electrometric amplifier with compensation in the negative feedback loop.

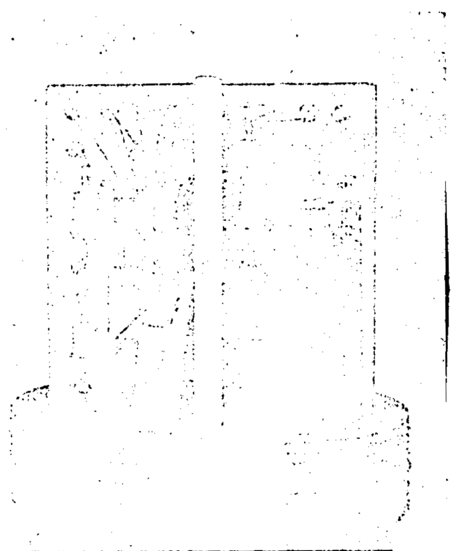

Figure 5. Miniature broad-band amplifier with screen removed.

Conclusion

In the case of the amplifiers which have been described the sensitivity to the current is limited by the current of the noises of the input circuit and the electrometric tubes I_{noise} in the table) and depends upon the band pass, the magnitude of high-ohmic resistance R and the type of electrometric tube. As indicated in ref. 2, in the case of amplifiers having a high degree of sensitivity to the current and to narrowed band pass ($f_{0.7} \leq$ 1-3 cps) the /107 flicker-noise of the electrometric tubes predominates. The level of the flicker-noise depends primarily upon the type and design of the tube, but, as tests have shown, the level can differ by 2-3 times even in the case of tubes of the same type. In order to increase the sensitivity to the current in the broad band it is advisable to increase resistance R in the feedback loop to such magnitudes at which it is still possible, by means of compensation, to obtain a given band pass. In this case the signal-to-noise ratio increases in proportion to the root of R. In regards to the method of compensating the frequency characteristic, both methods (positive feedback and insertion of a filter in the negative feedback loop) yield approximately the same results. The first method is constructionally more complicated and in some cases it is necessary to use an additional tube to produce the phase shift.

The noise was measured most accurately in a miniature broadband electrometric amplifier. In the case of a resistance of R = 10^{11} ohms in the 160 cps band a noise level is obtained which is less than $5 \cdot 10^{-14}$a from peak to peak or less than 10^{-14}a LMS. It exceeds the rated thermal noise of resistance R in the same band by not more than twice.

The magnitude of the zero drift depends to a great extent on the type of circuit and the temperature stability of its components. The greatest stability is obtained with push-pull symmetrical circuits with a twin electrometric tube in which wire-wound resistances are used. In the case of similar single-ended amplifiers the drift magnitude is 2-3 times greater. In the case of an electrometer with a semiconductor amplifier the drift was not measured but, according to the observations made during the equation, the drift is shown to be not very much greater than in the case of a tube-type electrometric amplifier. The voltage of the microphonic effect and its frequency depend not only upon the type of tube but also on the manner of mounting the input stage of the amplifier.

All the amplifiers (except the miniature broad-band amplifier) are built with conventional components (resistances MLT-0.5 and wire-wound resistances, condensors BM, MBM, KSO-1 and KTK) and have approximately the same dimensions. ULM resistors and MBM and KLS condensors are used in the last amplifier. The dimensions of the amplifier are reduced by one half, but this is not the limit.

The power needed by the amplifiers from the sources (battery or rectifier with stabilizer) does not exceed 5 watts. The greater part of the power is consumed in the dropping resistances of the filament circuits. The required power decreases a great deal when the filaments are supplied from a separate source (in the case of a miniature broad-band amplifier down to 0.3 watt and in the case of a semiconductor amplifier down to 0.5 watt). Thus, the tube amplifier, having somewhat beter parameters, may not be inferior to the semiconductor amplifier from the standpoint of economy.

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